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MICROCLIMATE COOLING FOR COMBAT VEHICLE CREWMEN (U)

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I. INTRODUCTION

At air temperatures above 28°C (82°F), human thermal comfort is best achieved without clothing; however, it may be essential if the human is exposed to contact with surfaces above 45°C (113°F), sunlight, blowing sand, drying wind, missiles and/or NBC agents. Increasing protection is associated with increasing thickness of barrier layers on the skin. Unfortunately, any barriers between the skin and the ambient environment reduce the ability to eliminate heat from the body.

a) BODY HEAT PRODUCTION

Heat production (M) at rest is about 1 Met (50 kcal of per square meter of body surface area per hour); an average man's heat production at rest is 90 kcal/hr or 105 watts. Normal work can double heat production and hard work can triple it. The sustainable "voluntary hard work" level is ~5 Met (425 kcal/hr or 500 watts), while 6 or 7 Met will exhaust the average man if sustained for a few hours.

b) BODY HEAT LOSS MECHANISMS

About 12% of the resting heat production is eliminated from the lungs by respiration. Another 12% is eliminated by evaporation of the body water diffusing through the skin; up to 0.6 kcal of heat is removed for each gram of water evaporated. Evaporation can, however, be blocked by ambient vapor pressures greater than the vapor pressure of water at skin temperature or by clothing which, even if permeable to water vapor, reduces the potential evaporative cooling by imposing insulation between the skin and the environment. The remaining 76% of resting metabolic heat production is eliminated from the body by convection and radiation in a comfortable environment. Elimination of the increased heat production during work is facilitated by the convective air motion generated by body "pumping", but in a warm environment most of the increased heat production is lost by production of sweat and its subsequent evaporation; even in a cold environment, about 42% of working heat production may be lost by evaporation.

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c) STILL AIR INSULATION; THE "CLO" UNIT

Even without clothing, there is a barrier layer of still air next to the skin. This still air film acts as insulation against heat exchange between the skin and the ambient environment; without body or air motion this external air layer (Ia) provides 0.8 clo of insulation. One clo unit of clothing insulation is defined as allowing 5.55 kcal/m^2/hr of heat exchange by radiation and convection (H:RC) for each $^\circ$C of temperature difference between the skin (at average skin temperature $\bar{T}$s) and ambient air temperature (Ta). Since the average man has 1.8 m^2 of surface area, his H:RC can be estimated as: H:RC = (10/clo) ($\bar{T}$s - Ta) [Eq. 1]; i.e. an 0.8 clo still air layer limits the heat exchange by radiation and convection for a nude man to about 12.5 kcal/hr (10/0.8) for each $^\circ$C of difference between skin and air temperature. Thus, producing 90 kcal/hr, a resting man will lose 11 kcal/hr (12%) by respiration, 11 kcal (12%) by evaporation of the water diffusing through his skin and will have a requirement to evaporate sweat (Ereq) to eliminate the remaining 68 kcal/hr if the Ta is less than 5.5°C (i.e. 68/12.5 kcal/hr/$^\circ$C) below $\bar{T}$s. The required sweat evaporative cooling (Ereq) can be estimated as: Ereq = M + (H:RC) [Eq. 2] where M is the heat produced during rest or work and H:RC is estimated by Eq. 1. Since a comfortable $\bar{T}$s is about 33°C (91.4°F), an increasing percentage of the body surface area will be required to be sweating with a Ta above 27.5°C (i.e. 33° - 5.5°).

The external air layer is reduced by air motion, approaching a minimal value of ~0.2 clo at air speeds above 4.5 m/s (10 mph). With this minimum air insulation (0.2 clo), 68 kcal/hr can be eliminated by a nude man at an air temperature only 1.4°C below skin temperature (i.e. 68/(10/0.2) = 1.36°) without sweating.

d) CLOTHING INSULATION

Studies of clothing materials have concluded that clothing insulation is a linear function of thickness; differences in fiber or weave, unless these affect thickness, have only minor effects on insulation. A typical value for clothing insulation is 1.57 clo per centimeter of thickness (4 clo per inch). Figure 1 displays the actual thickness of the intrinsic insulation layers found around three body segments (torso, arm and leg) with ordinary clothing; the contributions of the trapped air layers to the total thickness are far greater than the thickness contributed by the fabric layers. Even with foam materials, used in some protective ensembles, the trapped air between layers is the dominant factor in insulation. Since insulation is a function of thickness and this, in turn, is a function of the number of layers, each added layer of clothing will exert a characteristic increase in total insulation. Thus, most two layer clothing ensembles exhibit quite similar insulation characteristics regardless of differences in fiber, fabric type or layer thickness.

e) EVAPORATION THROUGH CLOTHING

Evaporative heat transfer through clothing also is limited by its thickness. The moisture permeability index (im) is a dimensionless unit with a lower limit value of 0 for an impermeable layer and an upper value of 1 if all the moisture that the environment can take up can pass through the fabric. Values of im approaching 1 are only found with high wind and no clothing, since moisture vapor transfer is

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limited by the characteristic value for diffusion of moisture through still air. An im value for typical clothing in still air is ~0.5. Water repellent treatments, very tight weaves and chemical protective impregnations reduce im significantly.

The evaporative heat transferred from the skin, through the clothing and external air layers, to the environment is not simply a function of the permeability index (im) but a function of the permeability index-insulation ratio (im/clo). The maximum evaporative heat exchange with the environment can be estimated, as in Eq. 1 for the H:RC of a man, as: $HE\ max = 10 \times im/clo \times 2.2\ (Ps - \phi a\ Pa)$ [Eq. 3] where Ps is the vapor pressure of sweat (water) at skin temperature, Ts; ϕa is the fractional relative humidity and Pa is the saturated vapor pressure at air temperature. Thus, the maximum evaporative transfer is a linear, inverse function of insulation even if not further degraded by specific chemical agent protective treatments which reduce permeability or by water repellent treatments.

f) THE "PHYSIOLOGIC PROBLEM" OF PROTECTIVE CLOTHING

The percent sweat wetted surface area (%SWA) is the ratio of the required evaporative cooling (Ereq) estimated by Eq. 2, to the maximum evaporative cooling ("Emax") estimated by Eq. 3; i.e. %SWA = Ereq/Emax [Eq 4] While a little sweating is not uncomfortable, as the body surface area wet with sweat approaches 20%, discomfort begins to be noted. Discomfort is marked with between 20 and 40% of the body surface sweat wetted and performance decrements can appear; they increase as %SWA approaches 60%. Sweat begins to be wasted, dripping rather than evaporating at 70%. Physiological strain becomes marked between 60 and 80% SWA; increases above that level limit tolerance even for fit, heat acclimatized men. Obviously, any conventional chemical protective clothing will pose severe tolerance limits since their im/clo ratios are rarely above 0.2. The basic problem is that skin temperature (Ts) must be maintained at least 1°C below deep body temperature (Tre) for the body to transfer enough heat from the body core to the skin.

Normally, under conditions of unlimited evaporation, skin temperature is about 3.3°C + (0.006° x M) below Tre. Thus at rest, when Tre is 37°C, the corresponding Ts is about 33°C. The 4°C difference between Tre and Ts allows each liter of blood flowing from the deep body to the skin to transfer 4 kcal of heat to the skin. Since Tre increases and Ts decreases with increasing M, it usually becomes easier to eliminate body heat with increasing work since the difference between Tre and Ts increases by about 1°C per 100 watts of increase in M. Thus, at a sustainable voluntary hard work level (M = 500 watts) each liter of blood flowing from core to skin can transfer 9 kcal to the skin, 225% more than at rest.

Unfortunately, any clothing interferes with heat loss from the skin and skin temperature rises, predictably, with increasing clothing. Core temperature (Tre) also rises when clothing is worn, as a function of the insulation induced rise in Ts and the resulting limited ability to transfer heat from core to skin. There is an even greater interference with heat loss from the skin when sweat evaporation is required (Ereq) but is limited either by high ambient vapor pressures (ϕa Pa), low wind or low clothing permeability index (im/clo) (cf. Eq. 3). As Ereq approaches Emax, skin temperature increases dramatically and deep body temperature begins to increase exponentially. Deep body temperatures above 38.2°C are considered undesirable for

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an industrial work force; at a deep body temperature of 39.2°C, associated with a skin temperature of 36° or 37°C (i.e. Ts converging toward Tre) there is a 25% risk of heat exhaustion collapse in fit troops. At an elevated Ts, and Tre of 39.5° there is a 50% risk of heat exhaustion collapse and as Tre approaches 40°, with elevated skin temperatures, almost all individuals are highly susceptible. Tre levels above 42°C are associated with heat stroke, a life threatening emergency.

g) GENERAL CONCLUSIONS AS TO NATURE OF THE PROBLEM

In essence, mission performance will be seriously degraded by CW protective clothing worn during heavy work in moderately cool environments, or at low work levels in warm conditions. Little reduction in heat stress is likely with any two layer protective ensemble, or any single layer vapor barrier system for protection against CW agents, unless some form of auxiliary cooling is provided.

Figure 2 is a 1963 chart of "Predicted Time to 50% Unit Heat Casualties" when troops wear a CW protective ensemble in either open (MOPP III) or closed (MOPP IV) state. This is expressed as a function of the environmental Wet Bulb Globe Temperature (WBGT) index. If hard work is involved, tolerance time to 50% heat casualties is between 1 and 2 hours, whether in MOPP III or MOPP IV, and almost without regard to ambient WBGT above 70°F. For moderate work, little problem would be anticipated with WBGT in the 70°F range for closed suit, or below 80°F for open suit. For light work the WBGT would have to reach 90°F for MOPP IV and about 97°F for MOPP III to incur 50% unit heat casualties in 5 to 6 hours.

II. A FIELD STUDY DEMONSTRATION OF THE PROBLEM

a) DESIGN OF THE STUDY

Several XM-1 tanks were available ~~at Yuma, AZ~~ to study the heat stress/CW protection problem under desert conditions. ~~Two Marine~~ tank crews volunteered as ~~subjects~~; they were superbly fit, well-trained, heat-acclimatized and motivated. A six day test was carried out; the first two days were for training, and resolving problems; the last four days comprised the data generating portion of the trial. Day 3 involved wearing the fully closed CW clothing system over the CVC uniform (MOPP IV); the vehicle hatches were left open, but the engine and ventilators were shut off. MOPP IV was also worn on the final three days of the study; the engine and ventilators were shut off and all hatches closed on these three days.

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b) ENVIRONMENTAL CONDITIONS

During the four days of actual test the temperature averaged 35°C (95° F) with 26% relative humidity; winds were from 4 to 13 knots, cloud cover between 13 and 30%. There was little build-up of tank interior temperature above ambient temperature, even during Days 4, 5 and 6 when the hatches were closed and ventilation shut off. On Days 1 to 3, when the hatches were open, there was only a small increase in interior humidity over exterior relative humidity, by about 10%; however, when the hatches were closed (Days 4, 5 and 6), the interior relative humidity rose dramatically.

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One uses WBGT index to describe the heat stress. On Day 3 the inside WBGT was actually lower than that outside the vehicle because of the reduction of the solar load component of WBGT. However, on Days 4 through 6 there was a substantial, progressive increase in interior WBGT throughout the exposure inside the vehicle, reflecting the build up in humidity as the men's sweat accumulated.

c) ACTIVITY (HEAT PRODUCTION) LEVELS

Prior to the field study, it was predicted that if activity were limited to moderate work (~200 kcal/hr) only heat exhaustion would be incurred with a few hours in the closed hatch conditions. Accordingly, only one 3 to 5 minute fire mission was performed every thirty minutes. The Driver was essentially at rest; his estimated heat production was about 100 watts (i.e. under 90 kcal per hour). The Loader was doing less work than either the Commander or the Gunner; the latter, who had the most sustained work during the 3 - 5 minute fire mission each half hour, is estimated to have had a heat production of, at most, 225 watts (200 kcal/hr).

d) METHODS

Each afternoon the volunteers were weighed nude. Thereafter, all fluid intake was measured using pre-weighed canteens. Ts and Tre and heart rate sensors were attached, the crew men were dressed in the uniform for the day and reweighed.

The tank was parked in the sun close to a building where all data collection equipment was located. The vehicle had been wired for temperature measurements, and a network of cables connected from the vehicle to the measuring and monitoring equipment. This allowed on-line data collection and processing of Tre, Ts, interior and exterior air temperatures (DB), wet bulb temperatures (WB) and 2 measures of heat stress, the standard WBGT (FSN #6665-00-159-2218) and a new "BOTSball" WGT (FSN #6665-01-103-8547). The data were continuously recorded and graphed on-line. Heart rate was measured at appropriate intervals using a standard EKG. The crewmen entered the vehicle fully dressed; once inside it would have been impossible for them to dress in the CW protective clothing.

e) PHYSIOLOGICAL RESULTS

The rectal temperature (Tre) mean weighted skin temperature (MWST), the air (DB) and wet bulb (WB) temperatures and the WBGT and BOTSball temperatures are presented for Days 3 to 6 in Figure 3. All men wore the MOPP IV configuration.

On Day 3, Tre stayed low, even though all ventilators were shut off, because the hatches were open. One can see ripples associated with the 5 minute fire missions, especially in the skin temperatures of the Gunner and Commander. The men had no difficulty completing the scheduled exposure.

On Day 4, with hatches closed a very different pattern emerges; although there is a relatively constant difference between the interior and exterior air temperature (DB), the interior wet bulb (WB) rises dramatically. Since the non-ventilated wet bulb makes up 70% of the WBGT and BOTs indices, both of these show steeply rising heat stress. The effects of this stress are immediately notable in the steeply rising skin temperatures, and more slowly responding but nevertheless increasing deep body temperatures. Within 30 minutes, we detected errors in the

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Commander's directions for the fire mission and within the first hour he noted he was "making dumb mistakes". Water intake was strongly encouraged; up to 3 canteens an hour were ingested. Despite these attempts to maintain hydration and a high degree of motivation and leadership, after 80 minutes the Gunner slumped back in his seat, tore off his gas mask and indicated that he could not continue. The Commander and Gunner had voiced complaints for some time, felt chilled, were a little dizzy, but had not reached the criteria for removal; H.R. $\geq$ 180 b/m; Tre $\geq$ 39.5^{o} or Ts $\geq$ Tre. They had continued despite increasing discomfort. Although not at the criterion for termination, this voluntary discontinuance by the Gunner was not capricious; his final heart rate was 178 beats per min.

Essentially similar exposure conditions prevailed on Day 5, but the men wore a vest supplied with cooled water; this removed heat at a rate of about 100 watts from each man. Although the interior environmental humidity build-up did occur, there was little or no rise in Tre; $\bar{T}$s were extremely low. The men completed the full exposure without difficulty, without error and without discomfort.

Day 6 was a repeat of the Day 4 exposure. The ambient conditions were milder (WBGT was 35^{o}C on Day 4 versus 33.4^{o}C on Day 6) so that it took longer, but again it was the Gunner who, at 124 minutes of exposure, was unable to continue. This voluntary intolerance occurred as his skin temperature converged to his deep body temperature (cf Fig 3). As on Day 4, there were fire command errors, and subjective discomfort and complaints beginning early and increasing throughout the exposure, but the men did their very best to complete the full exposure.

The heart rate is perhaps the best expression of the combined effects of work, environment and clothing on the crewmen. On Day 3, with open hatches and ventilators off, heart rates were relatively steady but the average for the 4 man crew was above 100 beats per min. In contrast, on Days 4 and 6 heart rate rose linearly, reaching a peak average of 150 beats per min after 80 minutes on Day 4 and about 135 beats per min at 124 minutes on Day 6. When auxiliary cooling was provided, the average heart rate of the group was less than when the hatches were open throughout the exposure on Day 3.

On Day 3, with hatches open but with the men in full MOPP IV configuration, the sweat evaporation was not substantially different than on Day 1 when only the CVC uniform was worn, but it was achieved at a much greater expense in sweat production. With the hatches closed on Days 4, 5 and 6, the evaporation was stringently limited; the ratio of the amount of sweat able to be evaporated per unit of production (E/P) clearly showed the relative inefficiency of sweat elimination of body heat for Days 4 and 6; these were in the 20 $\pm$ 20% range, in contrast to the 30 to 50% values with auxiliary cooling on Day 5 or with open hatches of Day 3, and the 60 to 80% of Day 1 with just the CVC uniform. Sweat rate on Day 4 averaged 2 kg (4 1/2 lb) an hour; sweat rate for the Loader and Tank Commander exceeded 3 kg (6 1/2 lb) during the 80 minute exposure. The demands for water to replace these sweat losses can be contrasted with the average 0.63 kg/hr (1.4 lbs/hr) of sweat produced when auxiliary cooling was available. There is a reduction in drinking water requirement of between 1 and 1.5 liters an hour with auxiliary cooling.

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f) PERFORMANCE RESULTS

With the closed hatch conditions on Day 4, the men knew they were in troublehalfway through. At the end some felt they could only continue for another 10 or 15 minutes, except the Driver who was having little problem because of his low work rate. Estimated ability to perform was decremented by 25% for the Loader, and by more than 50 to 60% for the Gunner and Tank Commander. With auxiliary cooling on Day 5, the men had no problem completing, and felt they could continue for 3 to 4 hrs; there was little or no decrement in ability to perform the missions.

g) SUMMARY AND CONCLUSIONS FROM THE FIELD TRIAL

Significant heat stress was demonstrated, at a level to produce early performance decrements and, eventually, subjective inability to continue; this was fully supported by physiological data as being a valid endpoint for performance capability. This occurred under relatively modest ambient environmental heat conditions, and was most identifiable when the hatches were closed and the ventilators and blowers shut off. Auxiliary cooling using a water-cooled vest was clearly demonstrated as capable of alleviating the heat stress.

In conclusion, we have identified a clear mismatch between the ability of a crewman dressed in CW protective clothing and the simple demand that he perform an extremely light fire mission when ambient conditions (expressed as the WBGT) are in the 32 to 35°C (90 to 95°F) range. ~~In this study~~, these occurred inside the XM-1 only when the hatches were closed and the blowers shut off.

III. EVALUATION OF POSSIBLE SOLUTIONS

When one identifies such a mismatch between the man's capabilities and the demands of his mission, there are generally only three classes of solution: 1) modify the man; 2) modify the clothing or equipment; and/or 3) modify the mission. Everything possible to improve the tolerance of crewmen had been done in this test; the men were fully heat acclimated, had good training and practice wearing chemical protection, excellent physical fitness, superb motivation and leadership, and drank as much water as possible. This leaves only the latter two classes of solution to deal with the problem. First, it should be possible to re-design the tank ventilation system to avoid the interior humidity (and potential temperature) build-up when the hatches are closed. The only other simple solution is to revise tactics so as to minimize any closed hatch, ventilators off operation, limiting duration of such conditions to not more then 30 minutes. As with a revision of the tank ventilation system, this solution approach will not solve the heat stress problem globally, but it will reduce the range of environments in which it will be experienced. A suitable, and in some ways more functional, alternative is to provide some form of auxiliary cooling directly to the crewmen. A properly designed system will eliminate heat stress, conserve large amounts of drinking water and allow unimpaired performance across any climatic range, even in the Arctic if provision is made for heating the heat transfer medium.

IV. LABORATORY STUDIES ON AUXILIARY COOLING

Laboratory studies were carried out to evaluate a variety of modes of auxiliary cooling; in all, four approaches were evaluated: 1) Five water-cooled undergarments; 2) an air-cooled vest; 3) an ice packets vest; 4) a wettable cover.

a) EXPERIMENTAL METHOD

All cooling systems were dressed on an electrically heated copper manikin; its skin temperature is controlled by a sensor and proportional controller. A "skin" made out of "T-shirt" material is formfitted to the manikin; this "skin" is left dry for experiments requiring a dry skin condition and completely wetted to provide a 100% wet, maximal sweating, skin condition. All auxiliary cooling systems were worn directly over the manikin "skin" and under a CVC ensemble with a complete charcoal in foam, overgarment chemical protective suit, except that the wettable cover was worn directly on top of a totally impermeable (plastic) chemical protective suit. The electrical power required to maintain constant skin temperature was taken to be equivalent to the heat loss, through the clothing, any other covering items (mask, hood, etc.) and associated trapped and surface still air layers, to the ambient environment.

1. WATER-COOLED UNDERGARMENTS

The five water-cooled undergarments included: a water-cooled cap; a water-cooled vest; the water-cooled cap and vest; short, and long water-cooled undergarments. None provided cooling to the hands and feet. These water-cooled undergarments were worn over the completely wet (maximal sweating) manikin skin. The cooling water flow rate was 22.7 kg/h (378 ml/min) for the water-cooled cap, vest and cap w/vest, and was 63.6 kg/h (1L/min)for the short and long water-cooled undergarments. Cooling water inlet temperatures ranged from 7 to 28°C.

Figure 4a gives the range of cooling provided by each of the five water-cooled undergarments for a completely wet (maximal sweating) skin condition versus the cooling water inlet temperature. The rate of increase in cooling, with decrease in cooling water inlet temperature is: 3.1 w/°C for the watercooled cap; 4.4 w/°C for the water-cooled vest; 7.5 w/°C for the water-cooled cap w/water-cooled vest; 17.6 w/°C for the short, water-cooled undergarment; and 25.8 w/°C for the long, watercooled undergarment. At cooling water inlet temperatures above 10°C (probably too low for "comfort" under most conditions) the water-cooled cap did not provide 100w (86 kcal/hr) of cooling; both the water-cooled vest and the water-cooled cap w/water-cooled vest could provide 100w of cooling. Both water-cooled undergarments (short and long) could provide as much as 400w of cooling. A "comfortable" cooling water inlet temperature of 20°C should provide 46w of cooling using the water-cooled cap; 66w using the watercooled vest; 112w using the water-cooled cap w/water-cooled vest; 264w using the water-cooled short undergarment; and 387w using the long water-cooled undergarment.

The results demonstrate the obvious conclusion that cooling increases with an increase in body surface area covered by a water-cooled undergarment. However, our findings that a) with more skin area covered by a water-cooled undergarment, less area is exposed to receive heat from a hot

environment and b) such cooling practically eliminates the effects of adding protective clothing, were not obvious and, indeed, require confirmation with human studies.

2. AIR-COOLED VEST

A hot chamber environment study was initiated using an aircooled vest to distribute cooling air within a CVC suit worn with a complete CW suit. Air flows studied were 6, 8 or 10 ft^3/min and the cooling air inlet temperature to the vest was either 10°C at 20% relative humidity or 21°C at 10% rh. The results are expressed in terms of: 1) the "total heat exchange watts" supplied to the manikin surface; and 2) the "cooling watt" rates. The "total watts" removed from all six manikin sections (head, torso, arms, hands, legs and feet) include both the cooling provided by the cooled air supplied to the air-cooled vest and also the heat exchanges of the total surface area of the manikin with the hot environment. The "cooling watt" rate is the difference between the electrical watts supplied to the torso, arms and legs sections of the manikin when the air-cooled vest is providing cooling to the manikin, and when it is not providing cooling. The experimental data was obtained during exposure to either a hot-humid environment of 29.4°C at 85% rh, or a hot-dry environment of 51.7°C at 25% rh.

The total heat exchanges over the completely sweating surface area of the head, torso, arms, hands, legs and feet when cooling air is supplied to the air-cooled vest are plotted against the cooling air flow rate in Figure 4b, part A; the cooling watts are plotted against the cooling air flow rate in Figure 4b, part B. As expected, both the total heat exchanges and the cooling watts increase with cooling air flow rate and decrease with increasing cooling air inlet temperature.

For an air inlet temperature of 10°C (at 20% relative humidity) and a flow rate of 10 ft^3/min, the total heat exchanges over the manikin surface would be 233w in a 29.4°C (at 85% rh) environment and 180w in a 51.7°C (25% rh) environment. Increasing the cooling air inlet temperature to 21°C (at 10% rh) would reduce the total heat exchanges to 148w and 211w, respectively. Either air inlet temperature easily provides 100 watts of cooling.

(3) ICE PACKETS VEST

The ice packets vest studied holds 72 ice packets; each packet has a surface area of approximately 64 cm and contains about 46 grams of water. These ice packets are secured to the vest by velcro tape. One experiment was conducted with 40% of the ice packets removed. The vest with these ice packets was frozen overnight in a walk-in freezer (air temperature about -20°C) and removed from the freezer about 2 minutes prior to dressing on the manikin. All clothing components dressed on the manikin were originally at the temperature of the chamber air, except for the ice packets vest.

Experimentally, the cooling watts equal the difference in electrical watts supplied when the ice packets vest is providing cooling to the torso and when the unfrozen ice packets vest, at chamber air temperature, is dressed on the manikin. Cooling rates provided (watts) versus time were determined for a completely wet (maximal sweating) skin condition for heat exposure in three hot environments.

Figure 4c shows the decrease in cooling from time 0 minutes, when the ice packets vest was dressed on the manikin, in each of three environments. These decreases in cooling watts with cooling time are based on an average torso temperature of 35°C. The cooling provided by each individual ice packet will vary with time and its contact pressure with the torso surface, plus any heating effect of the clothing and hot environment; the environmental conditions have an effect on both the cooling provided and the duration of time this cooling is provided.

In environments of 29.4°C (at 85% rh) and 35.0°C (at 62% rh), this ice packets vest is still providing some cooling after about four hours of operation. However, in an environment of 51.7°C (at 25% rh), any benefit is negligible after about three hours of operation. When 40% of the ice packets are removed from the vest, the cooling provided over the torso is negligible after two hours of operation. Since the ice packets vest does not provide continuous and regulated cooling over an indefinite time period, exposure to a hot environment would require redressing with backup, frozen vests every 2 to 4 hours when the ice in these packets was completely melted and water temperature approached skin temperature. Replacing an ice packets vest would obviously have to be accomplished when a crewman was in a stand-down position. However, this cooling is supplied noise free and independent of any vehicle energy source or umbilical cord that would limit a crewman's mobility. Its greatest potential appears to be for short duration missions, e.g. aircrewmen on short flights; its drawbacks include the need for a freezer to keep spare vests frozen.

(4) WETTABLE COVER

The wettable cover was simply a two piece cotton cover which extended from just above tops of the combat boots and the wrists to a V-neck at the top. The trouser legs, sleeves and neck opening were generously cut and thus were not in close contact with the totally impermeable, plastic CW protective uniform, which was worn over the combat fatigue uniform.

Predicted values of supplementary cooling, and of the minimal water requirements to maintain the cover wet, for a man wearing the experimental ensemble in various combinations of air temperature, relative humidity and wind speed are given in Figure 4d. A mean skin temperature of 37°C, which would be typical for a stressed man in an impermeable ensemble, has been assumed in these predictions.

V. NON-HEAT STRESS PROBLEMS OF PROTECTIVE CLOTHING

Having presented a variety of options for auxiliary cooling to reduce the heat stress of wearing CW protective garments, if not totally eliminate it under most operational environmental conditions inside (and outside) armored fighting vehicles, it seems appropriate to add that elimination of serious heat stress problems will not totally resolve the degradation in military performance associated with wearing such protective clothing systems. Table 1, an abstract of the operational degradation observed in a series of large scale field studies conducted by the various combat arms in the late 1960s suggests the performance decrements associated with wearing CW protective ensembles in the absence of any heat stress; the majority of

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these result from mechanical barriers to sensory inputs to the wearer and to barriers for communication between individuals. By redesigning the maneuver scenarios prepared initially by the various combat arms, heat stress was essentially eliminated, and it became feasible to assess other forms of performance decrements. The table compares the performance of troops wearing 1) normal combat clothing and equipment (MOP I), 2) CW protective ensembles "open", i.e. without hood, gloves and with all apertures open, but with gas mask (MOP II) or 3) fully encapsulated (MOP III) with mask, hood and gloves, and all uniform openings sealed, for four critical elements of combat: 1) fire power, 2) communications, 3) mobility and 4) support. There is a great deal of variability in the results of any such "large scale maneuver" field studies of operational performance, and some of the expected "overcompensation" can be noted; i.e. performance is actually improved slightly by imposing impediments that the troops are aware of and can make adjustment for. However, overall it is clear that elimination of heat stress, while it will allow mission performance to continue, will not totally eliminate the constraints imposed by CW protective clothing systems.

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Human subjects paticipated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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Table 1. OPERATIONAL DEGREDATION WITH CB PROTECTION WITHOUT HEAT STRESS

MOP (I / II / III)	FIRE POWER	COMMUNICATIONS	MOBILITY	SUPPORT
INFANTRY	Rounds per hit: M-16 3.4 / 3.9 / 8.6; (%) - / 9↑ / 59↑; M-60 10 / 3.2 / 10.7; (%) - / 4 / 7; M-79 3.3 / 3.0 / 8.4; (%) - / 4 / 58↑	Messages unanswered 4 / - / 10; Time to install wires 15' / 23' / 26 min; Getting specific man 1-2' / - / 6+ min; Voice versus hand signals - / - / 50%↑	Road march time - / - / 17%↑; March rate - / <6% / 10%↓; Assault time - / <10% / >100%↑; platoon leader 142%↑; first man 197%↑; last man 102%↑	Time to get medic 270%↑; M-16 maintenance 16%↑; CBR recon 8 min / - / 9.3 min; Ammo resupply 13 min / 30% / 67%↑
ARMOR: N.B.- MOP III also required closed hatch	Rounds per hit: M-73 - / NSD / -; M-85 - / 6%↑ / 100%↑; 105 - / 0.3x↑ / 0.6x↑; Zero main gun - / 1 min↑ / 3 min↑	Target identification # missed 1 / 7 / 25; 13% / 28% / 62%; # of transmissions - / 19↑ / 28↑; duration of transmissions - / 12%↑ / 6%↑	Road march time 9%↑; March rate 13%↓; Attack time 20%↑; Attack difficulty 3X	Boresight 1 min↑; Complaints: Gloves 33% maintenance, 27% loading; Mask/Hood 20% vision; CBR suit 16% movement
ARTILLERY:	Time from receipt at FDC to battery order: area adjust. - / 27%↑ / 137%↑; registration - / 100%↑ / 75%↑; transfer - / 35%↑ / 96%↑; Target location F.O. i.d. to call for fire 90 sec / 114 sec / 183 sec	In firing sections responses 26 OK / 11%↓ / 26%↓; Accuracy >95% / - / 65%; F.O. i.d. to end of mission 27 min / - / 40 min	Last unit across SP 192%↑; Clear hasty position 67%↑; Enter to all ready 31%↑	Filling sandbags 22 min / 25' / 35'; Wire splicing 5.3 min / 7.25' / 8'

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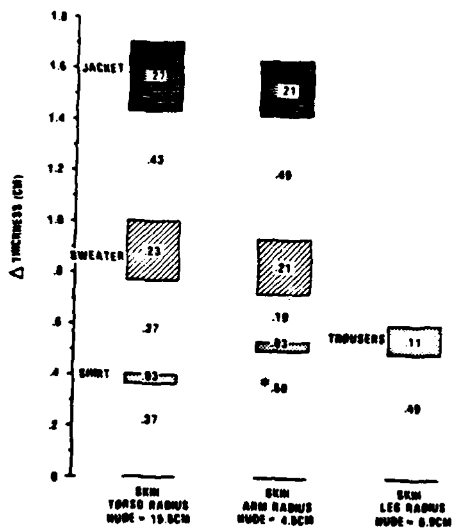
ENGINEERS: road repair, bridge building, demolition -NSD; voice commands repeated 2X as often in MOP III.



* THICKNESS OF TRAPPED AIR FILM > 0.5CM IS INEFFECTIVE BECAUSE OF INTERNAL CONVECTION

FIG. 1 CLOTHING THICKNESS AS A FUNCTION OF FABRIC AND TRAPPED AIR LAYERS.

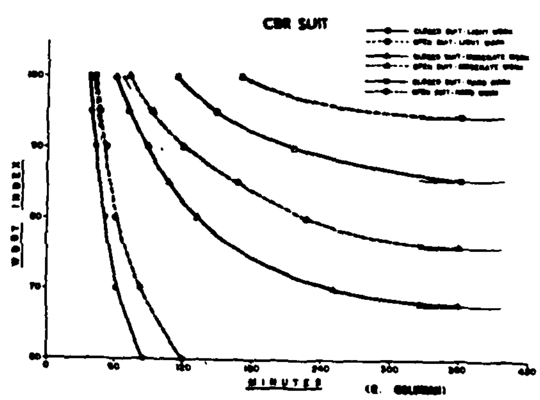


FIG. 2 PREDICTED TIME TO 50% UNIT HEAT CASUALTIES.

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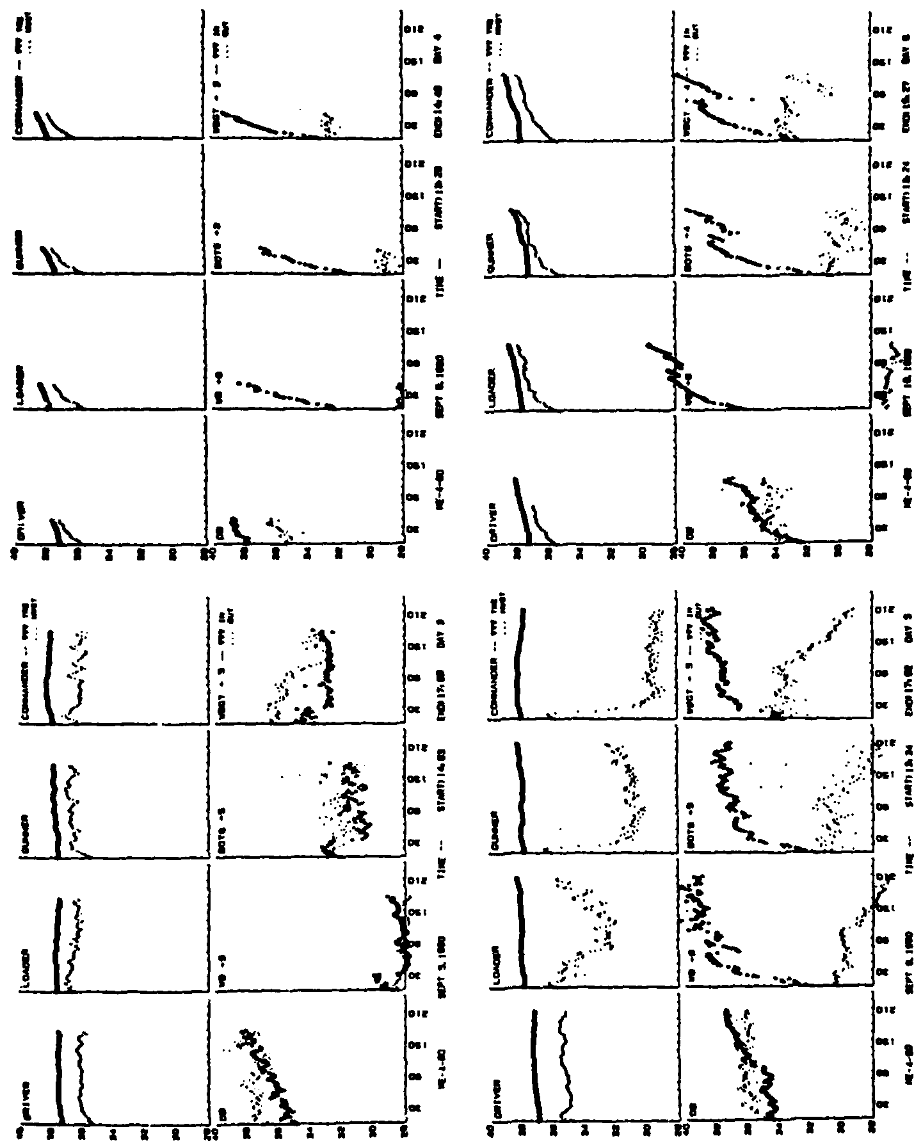

FIG. 3 INDIVIDUAL CREWMAN DEEP BODY (TRE) AND SKIN (WRIST) TEMPERATURES, AIR (DB) AND WET BULB (WB) TEMPERATURES AND THE TWO HEAT STRESS INDICES (WBGT AND BOTS BALL) INSIDE AND OUTSIDE THE TANK ON DAYS 3 TO 6.

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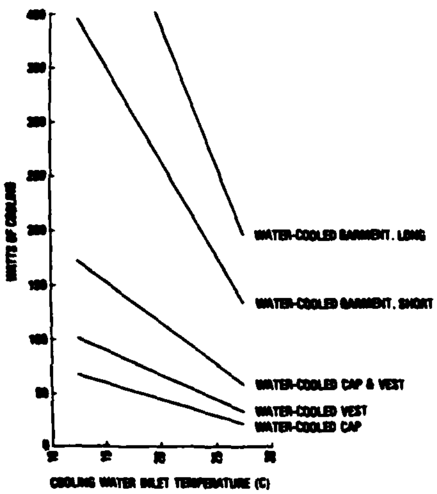

FIG. 4a LIQUID COOLING

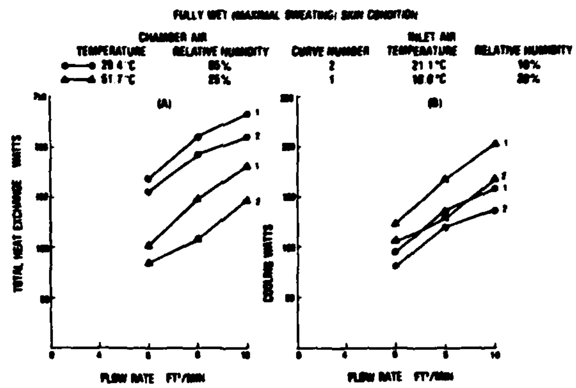

FIG. 4b AIR COOLING

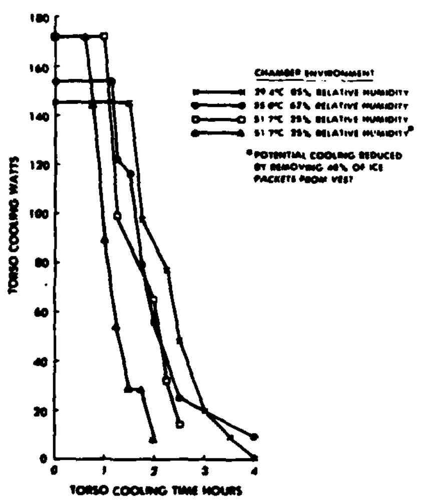

FIG. 4c ICE VEST COOLING

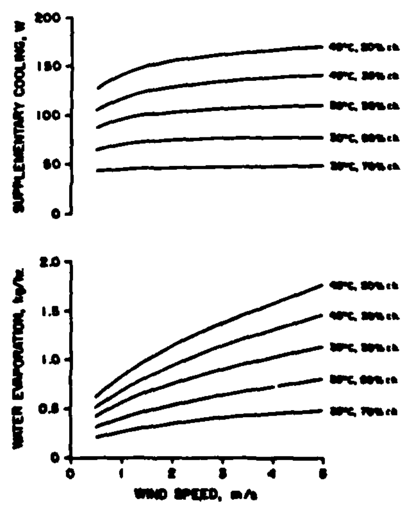

FIG. 4d PREDICTIONS OF SUPPLEMENTARY COOLING AND WATER REQUIREMENTS WITH WETTED COVER FOR FIVE TEMPERATURE-HUMIDITY COMBINATIONS.

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